Modeling Turbulent Air-Sea Exchange in High Winds

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LONG-TERM GOALS

The goal is to investigate, theoretically and through analyzing existing data, the role that sea spray plays in transferring heat, moisture, and momentum across the air-sea interface, especially in high winds. Ultimately, I plan to develop simple, fast, physics-based parameterizations for these air-sea fluxes for use in large-scale models, especially those simulating tropical and extratropical storms.

OBJECTIVES

1. By analyzing turbulent flux data sets, develop simple, fast parameterizations for the air-sea sensible and latent heat fluxes, the total enthalpy flux, and the surface stress in high winds, where sea spray is mediating all of these exchanges.

2. Theoretically extend these parameterizations to high winds, up to hurricane strength (~60 m/s).

3. Collaborate with large-scale modelers to implement and test these formulations in state-of-the-art coupled atmosphere-ocean models.

APPROACH

This work is theoretical and analytical; it has no experimental component. Andreas is the only CRREL participant, aside from an occasional undergraduate student; but he has been collaborating with large-scale modelers elsewhere—primarily Will Perrie at Bedford Institute, Dartmouth, Nova Scotia—to implement his spray parameterization in mesoscale storm simulations.

Microphysical theory establishes how rapidly spray droplets can exchange heat and moisture in a given environment. Theory also predicts how sea spray production should depend on wind speed. The analytical part involves developing parameterizations for the various spray transfer processes by simplifying model results or by synthesizing various data sets and observations. Checking the parameterizations against available data is also another aspect of what I call analytical work.

Conceptually, momentum and sensible and latent heat can cross the air-sea interface by two routes: as interfacial fluxes that are adequately parameterized by the COARE bulk flux algorithm (Fairall et al. 1996) and as fluxes mediated by sea spray. In low winds, say 10 m/s or less, the spray route is negligible. As spray concentration increases with increasing wind speed, however, the spray route

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becomes increasingly important until, in hurricane-strength winds, it is the dominant air-sea exchange route (e.g., Emanuel 2003; Andreas 2004a). I have been developing a unified algorithm that predicts the flux contributions through both routes.

My algorithm assumes that the total sensible ($H_{s,Tot}$) and latent ($H_{L,Tot}$) heat fluxes that would be measured by eddy-correlation instruments at a height above the spray layer are the sums of the interfacial (i.e., H_s, H_L) and spray contributions. My microphysical model (Andreas 1989, 1992) combined with an estimate of the spray generation function (Andreas 2002) predicts the nominal spray sensible ($\overline{Q}_S$) and latent ($\overline{Q}_L$) heat fluxes. With these contributions, the total fluxes are (e.g., Andreas and DeCosmo 2002; Andreas 2003)

$$H_{s,Tot} = H_s + \beta \overline{Q}_S - (\alpha - \gamma)\overline{Q}_L , \tag{1a}$$

$$H_{L,Tot} = H_L + \alpha \overline{Q}_L . \tag{1b}$$

The α, β, and γ are small, non-negative coefficients that ultimately tune the model to data. In a modeling sense, the total fluxes represented as the left sides of (1) would serve as the lower flux boundary condition for an atmospheric model.

My flux algorithm uses the COARE Version 2.6 algorithm (Fairall et al. 1996; Andreas and DeCosmo 2002) to compute H_s and H_L in (1). The $\overline{Q}_S$ and $\overline{Q}_L$ values in (1) come from my full microphysical model, but this model is too computer-intensive for large-scale modeling. Hence, I have greatly parameterized the results from that model such that my current flux algorithm predicts the spray sensible and latent heat fluxes, $Q_{S,sp}$ and $Q_{L,sp}$, from

$$\beta \overline{Q}_S - (\alpha - \gamma)\overline{Q}_L \equiv Q_{S,sp} = \rho_w c_w (T_s - T_{eq,100}) V_S(u_*) , \tag{2a}$$

$$\alpha \overline{Q}_L \equiv Q_{L,sp} = \rho_w L_v \left\{ 1 - \left[\frac{r(\tau_{f,50})}{50\,\mu m}\right]^3 \right\} V_L(u_*) . \tag{2b}$$

In these, ρ_w is the density of seawater; c_w, the specific heat of seawater; L_v, the latent heat of vaporization of water; T_s, the sea surface temperature; and $T_{eq,100}$, the equilibrium temperature of spray droplets that originally formed with a radius of 100 μm. Both $Q_{S,sp}$ and $Q_{L,sp}$ are in W/m^2.

Furthermore, in (2b), r is the radius as a function of time (t) of a droplet that started with a radius of 50 μm. In general, for any spray droplet,

$$r(t) = r_{eq} + (r_0 - r_{eq})\exp(-t/\tau_r) \tag{3}$$

is a good approximation. Here r_0 is the initial radius of the droplet, r_{eq} is its equilibrium radius, and τ_r is the e-folding time for the droplet's evolution to this equilibrium radius. In (2b), $\tau_{f,50}$ is the atmospheric residence time of a droplet that started with a radius of 50 μm. Thus, in essence, I

approximate $Q_{L,sp}$ from the behavior of 50-µm droplets. Likewise, (2a) estimates $Q_{S,sp}$ from the behavior of 100-µm droplets. Finally, in (2), $V_S(u_*)$ and $V_L(u_*)$ are empirical functions of the friction velocity, u_*.
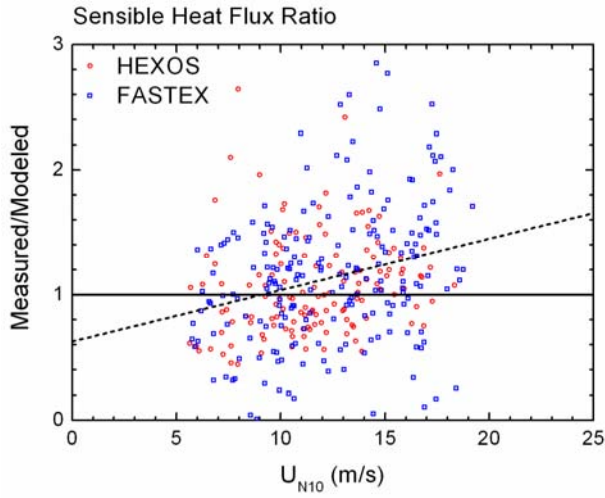

Fig. 1. Ratio of the measured-to-modeled sensible heat flux for the combined HEXOS and FASTEX set as a function of the neutral-stability wind speed at a reference height of 10 m. The modeled flux does not include any spray contributions. The dashed line is the least squares fit of the ratio to the wind speed and demonstrates that the measured sensible heat flux gets progressively larger than the modeled flux as the wind approaches 20 m/s. For wind speeds below about 10 m/s, the ratio is typically one: Measured and modeled fluxes are essentially equal.
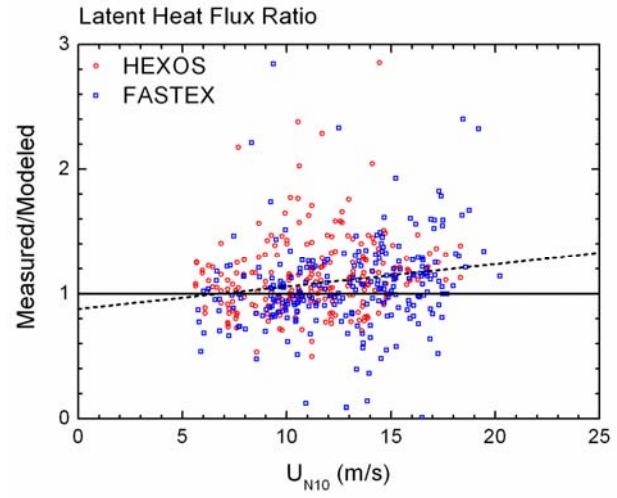
Fig. 2. As in Fig. 1, except this shows the ratio of measured-to-modeled latent heat flux, with no spray effect in the modeled flux. Again, the ratios cluster around one for wind speeds of 10 m/s and less, but the least squares line shows that the measured flux tends to be greater than the modeled flux as the wind speed approaches 20 m/s.

WORK COMPLETED

Andreas and DeCosmo (1999, 2002) identified a spray signature for winds, nominally, above 12 m/s in the turbulent heat flux data from HEXOS (the experiment to study Humidity Exchange over the Sea). To the HEXOS set, I have added the larger high-wind data set from FASTEX (the Fronts and Atlantic Storm Tracks Experiment; Persson et al. 2005). In the last year, I have pulled the spray signature out of this combined data set.

That analysis takes two steps. Figures 1 and 2 show the ratios of measured-to-modeled sensible and latent heat fluxes for the combined HEXOS and FASTEX set if I assume no spray effects in the modeled flux. That is, the modeled flux comes from (1) with $\alpha = \beta = \gamma = 0$. In both figures, the least squares line increases progressively above one as the wind speed increases. I interpret this behavior to

be evidence of spray-mediated heat and moisture transfer that becomes increasingly larger as the wind speed increases beyond 10 m/s.
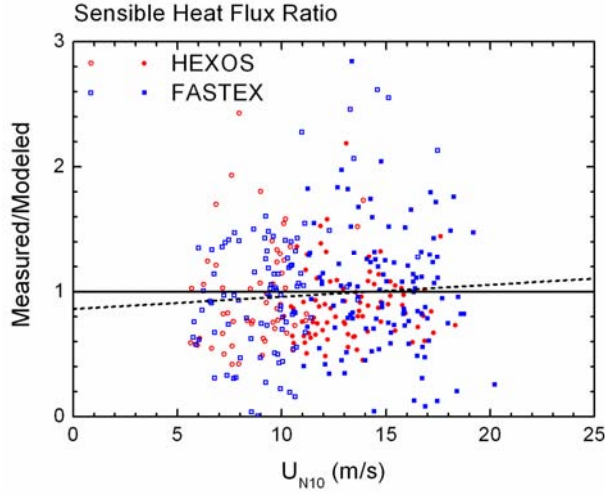

Fig. 3. The ratio of measured-to-modeled sensible heat flux, as in Fig. 1; but here the model includes spray effects with $\alpha = 1.5$, $\beta = 10.5$, and $\gamma = 0.2$ in (1a). The dashed line is again the least squares fit; but the slope is not statistically different from zero. That is, now the points do not depend on wind speed. The average ratio of all the points is 0.980, which is not significantly different from one. The filled markers denote cases for which the magnitude of the modeled spray flux is at least 10% of the magnitude of the modeled interfacial flux. Most points for wind speeds above 11 m/s are filled and, thus, imply a significant spray contribution to the total flux.
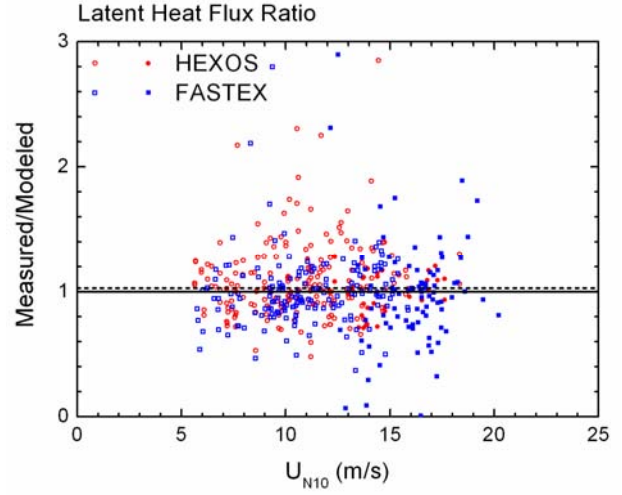
Fig. 4. The ratio of measured-to-modeled latent heat flux, as in Fig. 2; but here the model includes spray effects with $\alpha = 1.5$ in (1b). The dashed least squares line here is horizontal with a value of 1.031, which is thus the average value of the ratios plotted and is not statistically different from one. The filled markers again show cases with a 10% spray effect on the latent heat flux. Most markers above a wind speed of 13 m/s are filled.

To test this hypothesis, in the second part of the analysis, I try to account for these spray effects by adding spray to the modeled flux, as suggested in (1). Figures 3 and 4 are like Figs. 1 and 2, but now I have accounted for spray effects by setting $\alpha = 1.5$, $\beta = 10.5$, and $\gamma = 0.2$. In both of these figures, the least squares line has a slope that is not statistically different from zero, and the average of all the points plotted is not significantly different from one. That is, compared to Figs. 1 and 2, which ignored spray, Figs. 3 and 4 demonstrate that, by considering spray effects, I can explain both the magnitude and the wind speed dependence of the HEXOS and FASTEX data.

The filled markers in Figs. 3 and 4 denote cases for which the magnitude of the modeled spray flux is at least 10% of the magnitude of the corresponding modeled interfacial flux. That is, filled markers are cases when $\left| Q_{S,sp} / H_s \right|$ or $\left| Q_{L,sp} / H_L \right|$ was at least 0.1. For the sensible heat flux, most cases with wind

speeds above 11 m/s include a 10% spray effect; for the latent heat flux, most cases with winds above 13 m/s include a 10% spray effect. Consequently, this analysis corroborates the earlier analysis by Andreas and DeCosmo (2002) based just on the HEXOS data: Spray can contribute significantly to the air-sea fluxes of sensible and latent heat once the wind speed reaches about 12 m/s.
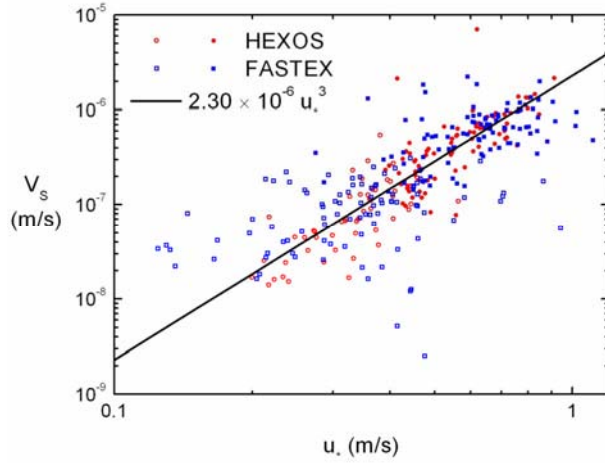

Fig. 5. *The wind function V_S in (2a) evaluated from the combined HEXOS and FASTEX data. V_S goes as the cube of the friction velocity; see (4a). As in Fig. 3, filled markers denote those cases with a 10% spray effect. Most markers for which u_* is above 0.5 m/s are filled.*
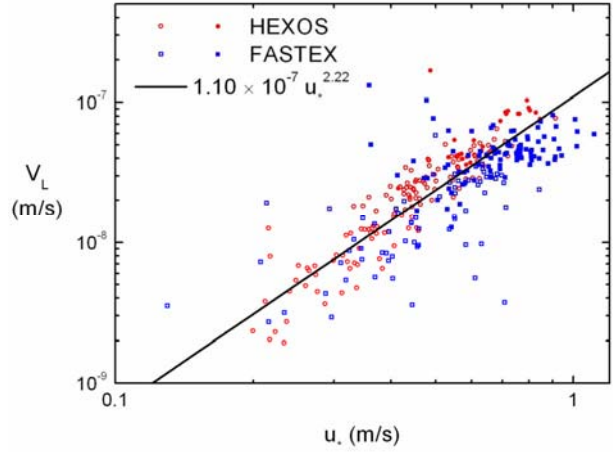
Fig. 6. *The wind function V_L in (2b) evaluated from the combined HEXOS and FASTEX data. V_L goes as the friction velocity to the power 2.22; see (4b). Filled markers again denote cases with a 10% spray effect. Most markers for which u_* is above 0.6 m/s are filled.*

RESULTS

Comparing Figs. 1 and 3 and Figs. 2 and 4 shows how spray affects the turbulent air-sea heat fluxes in only moderate winds. In gale force, storm, and hurricane winds, the spray contributions must continue increasing until they dominate the interfacial contributions. My calculations suggest that the crossover to spray dominance occurs at 10-m wind speeds between 28 and 32 m/s. In other words, in this wind speed interval, the spray sensible and latent heat fluxes become larger than the corresponding interfacial fluxes.

I have tried to keep my analysis theoretically based so we have some hope of extending my model up to wind speeds for which we have no reliable data. This is also the motivation for parameterizing the spray fluxes as in (2). The analysis on which Figs. 3 and 4 are based yields $Q_{S,sp}$ and $Q_{L,sp}$ in (2). From my new microphysical algorithms (Andreas 2005) and other parts of my spray model, I can calculate $T_{eq,100}$, $r_{eq,50}$, $\tau_{r,50}$ and $\tau_{f,50}$ for use in (2). Thus, from data, theory, and the model, I can evaluate the empirical wind functions $V_S(u_*)$ and $V_L(u_*)$ in (2). Figures 5 and 6 show the results, which are

$$V_S = 2.30 \times 10^{-6} u_*^3 , \qquad (4a)$$

$$V_L = 1.10 \times 10^{-7} u_*^{2.22} . \qquad (4b)$$

These give V_S and V_L in m/s when the friction velocity u_* is in m/s.

Equations (1)–(4), thus, constitute Version 3.1 of my spray bulk flux algorithm. From Figs. 5 and 6 and Equation (4), we see that both spray fluxes increase faster than u_* squared—primarily because the rate of spray generation increases approximately as the cube of u_* (Andreas 2002). In bulk flux algorithms for the interfacial fluxes (e.g., Fairall et al. 1996; Andreas and DeCosmo 2002; Andreas 2003, 2004b), on the other hand, the interfacial sensible and latent heat fluxes, H_s and H_L, increase only linearly with wind speed. Thus, again, we see how the spray-mediated fluxes can eventually dominate the interfacial fluxes as the wind speed increases.

IMPACT/APPLICATIONS

The unified turbulent flux algorithm that I have developed has three features that are not all present in any other air-sea flux algorithm: It explicitly recognizes two routes by which heat and momentum cross the air-sea interface, the usual interfacial route and the spray-mediated route; it has been verified against data; and it is theoretically based and, therefore, can be extrapolated to high-wind conditions, where we currently need an air-sea flux algorithm but have few reliable data on which to base an empirical one.

Developing such a high-wind air-sea flux algorithm is one of the central objectives of CBLAST. But we still need to see if such an algorithm improves predictions of ocean storms. I have been trying to answer that question, primarily through my collaboration with colleagues at Bedford Institute. Our simulations with an earlier version of my flux algorithm (Version 1.1; Andreas 2003) suggest that including the spray heat fluxes in a mesoscale atmospheric model gives better predictions for the intensity of extratropical storms than does a more conventional surface flux parameterization when central pressure and maximum surface-level wind speed are used as metrics for storm intensity (Li et al. 2003; Perrie et al. 2004a, 2004b, 2005, 2006).

TRANSITIONS

Besides the journal articles and conference papers that I have written to describe my work on sea spray and the resulting bulk flux algorithm, I have developed software "kits" that contains the instructions and FORTRAN tools necessary to implement this algorithm. Version 3.1 is the algorithm I have described here and is in my current kit. I have distributed this kit to several CBLAST collaborators—namely, Bill Frank at Penn State and Shouping Wang at NRL-Monterey—and to several others. Wang reports that my spray algorithm, indeed, increases the intensity of tropical storms compared to surface flux parameterizations in conventional mesoscale models.

The transition of my work that has progressed the furthest, however, is at Bedford Institute, where Will Perrie and his colleagues have introduced my unified surface flux parameterization into the Canadian mesoscale compressible community model (MC2) and have been simulating Atlantic storms with it. This work is already documented in several papers (Li et al. 2003; Perrie et al. 2004a, 2004b, 2005, 2006). Although these papers used Version 1.1 of my algorithm, Perrie and colleagues have also run simulations with Versions 2.0 and 3.1. They find that, during differing periods in the life cycle of storms, spray effects can compete with or even dominate other air-sea processes, such as wave drag.

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